Assessing the role of pull-apart basins for high-temperature geothermal resources in transcurrent tectonic setting: Sumatra and California compared

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ABSTRACT

Pull-apart basins formed as the expression of a releasing bend within a transcurrent tectonic setting, is commonly thought to play an important role in the occurrence of a geothermal resource, due to enhanced permeability around border faults, porous basin-fill sediment, and elevated heat flow due to crustal thinning, which support the development of high temperature geothermal system. Examples are the Salton Sea and Cerro Prieto geothermal fields in north western end of the Gulf of California. The thermal features of these fields are controlled by pull-apart basins while nearby extrusive domes hardly affect the resources. In contrast, in a subduction-related volcanic arc such as Sumatra, Indonesia, pull-apart basins are less important in influencing the resource potential of geothermal systems. An analysis of 14 intra-arc pull-apart basin along the Sumatran Arc and its associated geothermal system shows that there the resource is controlled by shallow intrusion beneath the flank of Quaternary volcanic centres. Rather than controls the upflow part, the pull-apart basin may influence the lower temperature outflow zones. Moreover, Sumatran intra-arc pull-apart basins are not accompanied by crustal thinning and associated elevated heat flow.

1. INTRODUCTION

Most of electricity-grade geothermal resources are convective systems with close affinity to magmatism and volcanic centres (Moeck, 2014; Stelling et al., 2016). The two most important factors which determine the nature of convection in this geothermal type are heat source and permeability. Not surprisingly, the most effective heat source is shallow plutonic intrusion (Santilano et al., 2015) which is common in magmatic provinces or along the volcanic arcs. The secondary permeability is important for the fluid circulation since in general the crystalline rocks and volcaniclastic units have small primary intergranular porosity and permeability. Most of the secondary permeability are related to natural fracture system due to brittle deformation such as faulting (Faulds et al., 2010), but some can be also created by leaching in hydrothermal alteration processes or diagenesis (Bogie et al., 2015).

Therefore, good understanding of both intrusion and nearby natural fracture systems is very important in the characterization and resource assessment of geothermal system during exploration stage, field development, and production. For the island of Sumatra, Indonesia, where the subduction-related volcanic arc occurs along regional strike-slip fault system under transcurrent tectonic, it is logical that associated geothermal systems are strongly influenced by the interplay of magmatism, volcanism, and brittle deformation, i.e. faulting.

In strike-slip fault system, pull-apart basin is prominent feature which accommodates strain in the irregularity within strike-slip fault system, such as fault bending or step-over (Aydin and Nur, 1982). It is thought to give extra reservoir frameworks for geothermal resource if the strike-slip fault coexists with volcanic centres (Muraoka et al., 2010). Enhanced permeability around the border faults, both master and transfer faults, porous basin-fill sediments, and elevated heat flow due to crustal thinning in the basin should be favourable for the occurrence of geothermal system. This paper is aimed to address the role of intra-arc pull-apart basin for high-temperature geothermal system in transcurrent setting with Sumatra as case study to test the aforementioned hypothesis. The findings are then compared to other geothermal systems associated to pull-apart basins around Gulf of California.

2. REGIONAL FRAMEWORK

2.1 Tectonic setting of Sumatra

From Late Neogene the tectonic of Sumatra is dominated by oblique convergence between Indian oceanic plate and Sundaland, a promontory of Eurasia (Figure 1). It leads strain partitioning (Chemenda et al., 2000) which accommodates compression in subduction and accretionary zone, and transcurrent in crustal-scale strike-slip fault system inland. The onset of strike-slip deformation, the Sumatran Fault System, was closely associated with the opening of Andaman Sea in NW and increasing subduction obliquity due to island clockwise rotation since Mid-Miocene (McCarthy and Elders, 1997).

In fact, the overriding plate is composed by several microcontinents which amalgamated during Palaeozoic and Mesozoic (Barber and Crow, 2003). Geologic inheritances from each tectonic blocks in form of pre-existing basement structures, and sutures bring in the heterogeneities in overriding plate, which strongly affect much younger structures, such as the Sumatran Fault.

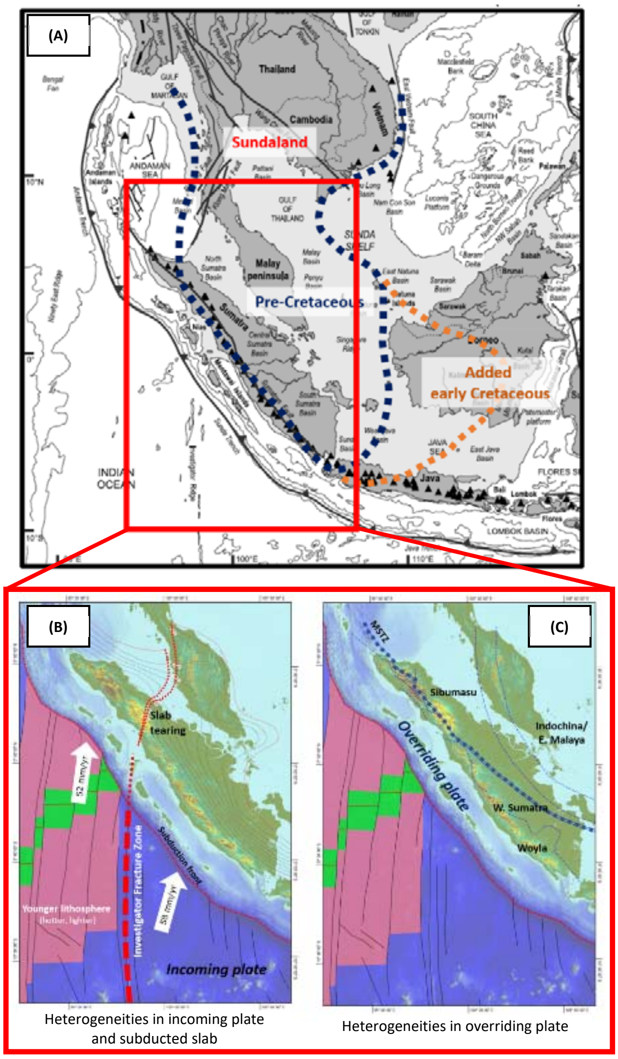

Figure 1: Tectonic setting of Sumatran subduction systems; A. tectonic blocks were amalgamated in Pre- and Early-Cretaceous (modified from Hall, 2011); B. Heterogeneities in incoming plate and subducted slab; note the inward deflection of trench line, and slab tearing which separates southern step and northern gentle subduction; green is inactive spreading centres, grey dashed lines are slab contour; C. Major tectonic blocks build Sumatra, and its suture; MSTZ is medial Sumatran Tectonic Zone

The heterogeneity exists in the incoming plate as well. the Investigator Fracture Zone, a remnant of transform structure which forms N-S oceanic ridge behaves indentor as well as weak zone. Moreover, younger lithosphere has higher temperature and lighter density, while the inactive spreading centres which experienced serpentinization have weaker rheology (Jacob et al., 2014). Those features tend to resist subduction and create inward deflection of the trench from regular arc shape (Figure 2). Seismic tomographic model shows that the subducted ridge also formed tearing in the slab (Hall and Spakman, 2015), separating step subduction dip angle in the south and more gentle dip angle in the north. This slab tearing has significant impact in magmatism below and within the overriding plate (Koulakov et al., 2016), while the differences in subduction dip angle responsible for different volcanic arc location with respect to the Sumatran Fault (Figure 2).

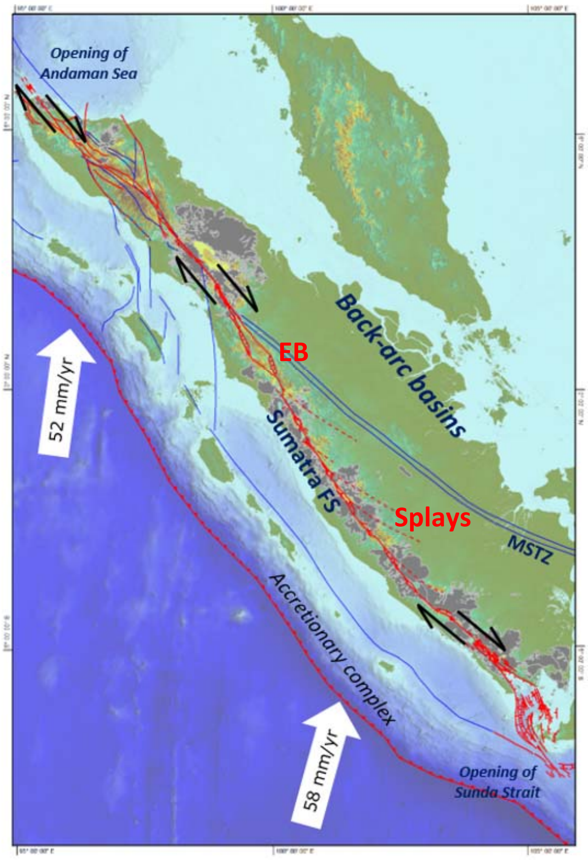

Figure 2: Sumatran Arc consists of Quaternary volcanic arc (grey shaded area) and The Sumatran Fault System, highly segmented and irregular dextral strike-slip fault system (red lines); it connects the opening of Sunda Strait in the SE with Andaman Sea in the NW; note the occurrence of series of WNW-ESE splays which are parallel to MSTZ; blue thin lines are fault system in fore-arc region

The Sumatran Fault System is NW-SE regional dextral strike-slip fault which runs along the island, parallel to the trench, linking the opening of Sunda Strait in its southern end to the spreading of Andaman Sea in its northern far end. It is highly segmented (Sieh and Natawidjaja, 2000) and strongly controlled by pre-existing basement structures (McCarthy and Elders, 1997). Local transtensional or transpressional deformation accommodates the strain between fault segments, or where the fault traces bends. In most of its trace this fault system has close proximity with Quaternary volcanic centres which related to subduction. Sieh and Natawidjaja (2000) suggests there is no relationship between young volcanoes and the fault based on random distribution of the volcanoes with respect to surface fault traces. However, other authors (Bellier and Sebrier, 1994; McCarthy and Elders, 1997; Muraoka et al., 2010) proposed the interplay between volcanism and magmatism, and strike-slip faulting. Together, the strike-slip fault system and its subsidiary structures, and Quaternary volcanic centres form distinct elevated morphology along most of the western half of the island known as Bukit Barisan range.

2.2 Tectono-volcanic subdivision of Sumatran Arc

Based on the spatial relationship between the Sumatran Fault System and Quaternary volcanic centres it is proposed to divide Sumatran Arc or Bukit Barisan range into three domains (Sutrisno et al., 2019, manuscript in preparation). This tectono-volcanic subdivision (Figure 3) resembles three structural domains of Sumatran Fault proposed by Sieh and Natawidjaja (2000). Volcanic-related geothermal systems occur in each tectono-volcanic domain have distinct plays, therefore proposed subdivision is essential for further geothermal system characterization.

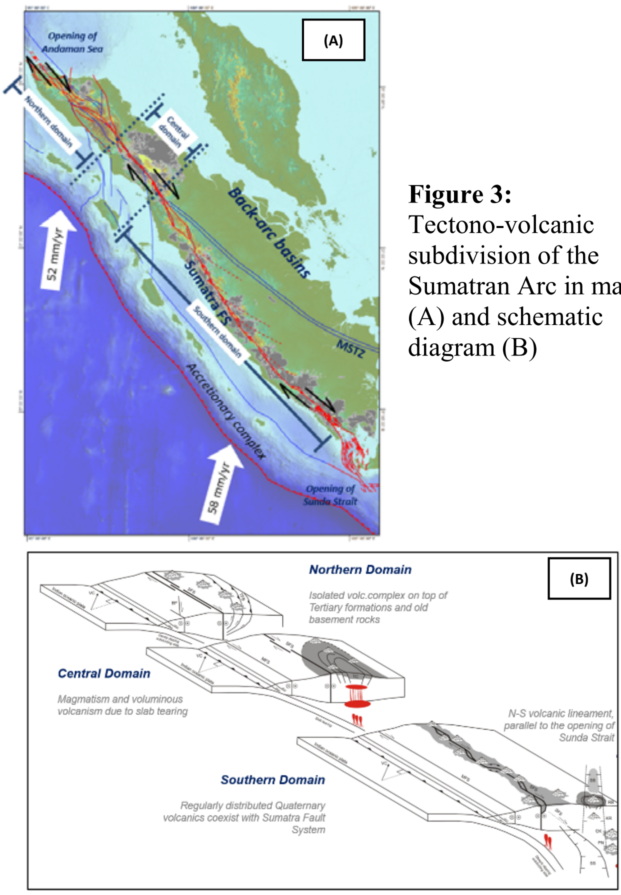

Figure 3: Tectono-volcanic subdivision of the Sumatran Arc in map (A) and schematic diagram (B)

Northern domain is characterized by the sifting of volcanic centres away from the trace of Sumatran Fault System toward back-arc basin. The volcanism in this domain was interpreted as product of southward subduction of Andaman oceanic plate beneath Sumatra (Gasparon, 2005). However, images of subducted slabs beneath Sumatra from seismic tomography disapprove previous interpretation (Hall and Spakman, 2015), while show that the shifting of volcanism is related to more gentle subduction sip angle. Volcanic centres have isolated distribution on top of thrust-fold belt of Pre-Tertiary basements and Tertiary formations. This setting implies that most of geothermal systems occur in the flank of volcanic centres with limited influence from Sumatran Fault, except in the northern end of this domain where the volcanism shifts back toward the Sumatran Fault and strongly controlled by conjugate fault system within strike-slip setting.

Toba Caldera dominates the central domain. Tearing in the slab act as window which for mantle upward flow, leads to voluminous magmatism in the base of lithosphere, as well as within the crust, as indicated by geophysical model (Koulakov et al., 2016) and petrologic data (Gasparon and Varne, 1995). The regional uplift around Toba Caldera may also associated with thermal expansion of shallow accumulation of magma beneath the region. In this domain geothermal systems are associated with resurgence volcanism around the caldera margins.

Coexistence of Quaternary volcanic centres and its extrusive rocks with the Sumatran Fault System marks the southern domain. Some volcanic centres, both active and inactive, are located close to, main strike slip fault strands, transtensional, or transpressional area between segments of the Sumatran Fault. This spatial proximity between the regional fault zone and volcanism influences the geothermal systems within.

3. INTRA-ARC PULL-APART BASIN AND VOLCANIC GEOTHERMAL SYSTEM ALONG SUMATRAN ARC

All but one intra-arc pull-apart basins which are discussed in this paper are located in the southern domain. Summary of 14 studied intra-arc pull-apart basins is presented in Table 1.

3.1 Geometry of pull-apart basin

Geologic inheritances from long deformation history of Sumatra, such as suture between tectonic blocks, inactive shear zone, and pre-existing basement structures strongly influence much younger dextral strike-slip Sumatran Fault System. As a result, Sumatran Fault System is highly segmented with many irregularities along the fault.

WNW-ESE oriented Medial Sumatran Tectonic Zone (MSTZ) is an inactive shear shore separates Sibumasu from West Sumatran Block (Barber and Crow, 2003). It strongly affects regional structures in both Sumatran arc and back-arc regions. MSTZ was responsible for the occurrence of Equatorial Bifurcation (Figure 2), much larger dextral over-stepping in Sumatan Fault which then reconnected back to main fault strand by elongated extensional structures, Rao and Panyabungan Graben.

Series of WNW-ESE splays from main NW-SE oriented Sumatran Fault (Figure 2) are also interpreted as reactivation of older basement structures parallel to

MSTZ. These structures are continuous to back-arc basins as reported by Pulunggono et al (1992). The Sumatran Fault is slightly deflected when it intersects these WNW-ESE oriented structures, creates fault bending or step-over. Pull-apart basin is then created when the step-over is dextral.

Table 1: Summary of 14 studied intra-arc pull-apart basins in Sumatran

Pull-apart basin	Geometry						Remarks on pull-apart basin	Nearby volcanic center (areal in km2)	Distance of volc. centre to basin (km)	Basin-fill deposit	Assoc. geothermal system	Remarks on geothermal system
	Length (km)	Width (km)	L/W	Area (km2)	Depth (m)							
Ulubelu	7	6	1.2	54	800	Gravity (Daud et al., 2000)	NW-SE cross-basinal fault	G. Rindingan (55 km2); several smaller monogenetic domes in the south	7	Central to medial	Ulubelu	Upflow in the flank of G. Rindingan, flows out southward; NW-SE cross basinal fault as permeable pathway as well as western margin of geothermal system
Suwoh	11	7	1.6	90	2200	Gravity (EBTKE, 2017)	NW-SE cross basinal fault (not so obvious, indicated by river channel)	G. Sekincau (77 km2); several smaller monogenetic domes in the south	15	Distal, interlayered with aluvial deposits	Suwoh and Sekincau	Geothermal systems in the flank of G. Sekincau; several systems along basin margins (Suwoh) may be controlled by monogenetic domes
Ranau	10	12	0.8	125	N/A		Uncertain whether it is pull-apart basin or collapse caldera	G. Seminung (23 km2)	7	N/A (covered by lake)	Talaga Ranau	Dilute warmsprings along the lake shoreline in the slope of G. Seminung; likely controlled by volcano
Talang Kemang	31	6	5.2	174	N/A		-	G. Kabaa (86 km2)	35	Somepart are covered by Quternary volcaniclastics	Kabaa	Few warmsprings along NW border faults; maybe distal outflow from G. Kabaa
Hululais	36	3-7	7	199	N/A		Wider toward SE side	G. Hululais (29 km2) and G. Bukitdaun (63 km2)	7-9	Somepart are covered by Quternary volcaniclastics	Hululais, Tambangsawah, Bukitdaun	Upflows are related to G. Hululais (and G. Bukitdaun) indicates by fumaroles on its flanks; Tambangsawah Cl-springs as distal outflow in NW border faults (23 km away from upflow), or deep-circulating system
Sungai Penuh	47	10	4.7	360 (min) - 550 (max)	N/A		Wider toward SE side; SE half part is uncertain as part of basin or not as it is covered by volcaniclastics and domes, min. area excludes this part	G. Kunyit (33 km2)	15	Somepart are covered by Quternary volcaniclastics	Semurup and Lempur	Lempur is an upflow in the volcano flank; Semurup (27 km away) maybe distal outflow or deep-circulating fluid along border faults
Muaralabuh	36	3-10	5	218	2000	Well data, conceptual model (Mussofan et al., 2018)	Wider toward SE side; dual depocenters are reported (Mussofan et al., 2018)	G. Patahsembilan (50 km2) and other volcanic centres	7	Somepart are covered by Quternary volcaniclastics	Muaralabuh	Upflows are indicated by flank fumaroles, and distal outflows in the basins
Gunung Talang	10	5	2	71	N/A		Lake Diatas and Lake Dibawah may be separated by cross-basinal fault	G. Talang (68 km2)	5	Central-medial	G.Talang-Bukitkili	Geothermal systems are controlled by volcanism; circulates outside the basin with minimum influence from the basinal faults
Singkarak	23	7	3.3	108	N/A		-	-	-	N/A (covered by lake)	Singkarak	Dilute warmsprings
Rao Graben	38	8	4.7	265	N/A		Eastern extensional graben in Equatorial Bifurcation Fault System	-	-	Aluvial	Panti and Simisuh	Dilute warmsprings, fault-controlled deep circulating systems
Panyabungan Graben	45	7	6.5	300	1500	Gravity (Sagala et al., 2016)	Western extensional graben in Equatorial Bifurcation Fault System	G. Sorik Marapi (45 km2)	12	Somepart are covered by Quternary volcaniclastics	Sorik Marapi	Upflows are related to G. Sorikmarapi indicates by acid manifestations on its flanks; Cl-springs as distal outflow; systems are compartmented by graben structures in the SE side of Panyabungan basin
Sarulla	42	3	14	97 (excl. Sibualbuali)	2200	Gravity (Hickman et al., 2004)	Very narrow pull-apart systems	Namora-i-Langit complex (40 km2), Sibualbuali 80 km2)	5	Somepart are covered by Quternary volcaniclastics	Sarulla systems (Namora-i-Langit, Silangkitan, Donotasik, Sibualbuali)	Except Silangkitan which is controlled basin's border fault, all systems are mainly controlled by volcanism around the basin
Tarutung	7	3	2.3	28	1300	MT (Niasari et al., 2015)	-	G. Martimbang (10 km2)	5	Mainly aluvial deposits	Sipoholon	Dilute warmsprings
Kutacane	76	9	8	500	N/A		Located in the Northern Domain	G. Kembar (43 km2)	14	Aluvial deposits	Gunung Kembar	Dilute warmsprings as distal outflow from G. Kembar

Occurrence of these splay structures also cause the tendency of pull-apart basins to be wider toward its SE-ends. It is observed clearly in Hululais, Sungai Penuh and Muaralabuh (Table 1). The width of those basins range from 3 km in its NW end, then widen up to 7-10 km in the SE end. Considering irregularity of its shape, it is difficult to apply shape classification proposed by Mann et al (1983) to describe studied pull-apart basin.

The size of pull-apart basins varies from less than 30 km2 to as large as 500 km2, with average areal extent is 140 km2. Depth of those basins ranges from 800 m to more than 2000 m, although available data are very limited to know exactly the overall depth range. More than half of those basin have length to width ratio (L/W) much larger than 3, the general value for L/W for pull-apart basin as proposed by Aydin and Nur (1982). Therefore, most of the pull-apart basin have elongated shape resembles rhomboidal to stretched rhomboid in classification of Mann et al (1983). The most extreme cases are Ranau and Sarulla.

Ranau has L/W much less than 3. This value and its peculiar shape, as it is too perpendicular to master strike-slip faults, raise uncertainty whether it is really pull-apart basin, or collapse caldera which latter intersected by strike-slip faulting. Sarulla is in other extreme side as its L/W is 12, indicates that this pull-apart basin is very narrow and extensively stretched. This extreme L/W may be also

3.2 Cross-basinal fault and dual depocenters

Cross-basinal faults are observed in several pull-apart basins. In Ulubelu, NW-SE cross-basinal fault acts as permeable pathway for geothermal convective flow and intersected by several productive wells. In Suwoh same structure is interpreted from a river flows inside the basin. In Gunung Talang, cross-basinal fault separates two depression lakes.

The basins with observed or interpreted cross-basinal fault consistently have small L/W value. It is in agreement with Van Wijk et al (2017) who based on numerical modelling concluded that elongated pull-apart basin with large L/W is less likely to form cross-basinal fault which connect the tip of two over-stepping master faults.

In Muaralabuh, conceptual model contrained by wells and confirmed by gravity anomalies indicate the occurrence of two sub basins separated by horst in between (Mussofan et al., 2018). This is in agreement with results from analogue modelling for transtensional setting with master faults are slightly oblique to transcurrent movement (Wu et al., 2009).

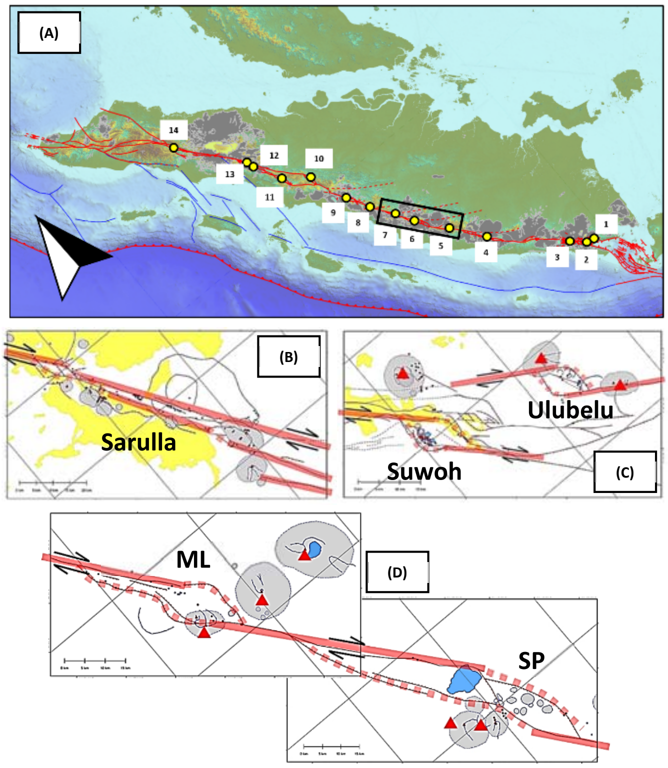

Figure 4: A. Location of pull-apart basins which are summarized in Table 1; Ulubelu (1), Suwoh (2), Ranau (3), Talangkemang (4), Hululais (5), Sungaipenuh (6), Muaralabuh (7), Gunung Talang (8), Singkarak (9), Rao Graben (10), Panyabungan Graben (11), Sarulla (12), Tarutung (13), and Kutacane (14); B. Sarulla, an elongated basin with anomalously high L/W; note that it is the highest known geothermal potential in Sumatra; C. Ulubelu and Suwoh basin which have small L/W; D. Muaralabuh (ML) and Sungaipenuh (SP) with irregular basin shapes as it is widen in SE side; grey circles is stratovolcanoes with red triangle represents eruption centres

3.3 Basin fill deposit and distance to volcanic centres

Basin fill deposits within intra-arc basins are determined by the distance of nearby volcanic centres to the basins. Minor influence from volcanism is expected in the basin located far from volcanoes. The basin is filled mostly by alluvial or lacustrine sediments with minor influx of extrusive volcanic rocks with medial to distal facies consists of fine grain volcaniclastics or laharic deposit. Both sediments and volcaniclastics in this setting tend to be clay rich. As it is underfilled by volcanic rocks, the basin outlines are still distinctly observable.

In contrast, if volcanic centres are relatively close to basins, or located exactly along the basin margins, then the basin receives significant amount of extrusive volcanic rocks to fill in. The volcanic facies of those basin fills are central to proximal, dominated by breccia, welded ignimbrite, and lava. Overfilled basin with thick volcanic sequences bury the whole basin is difficult to recognized as the basin original outline is obscured by the volcanic rocks.

As happen in Ulubelu, Gunung Rindingan volcanic centre is located at the northern margin of the small pull-apart basin. It is buried by volcanic sequences and the basin existence can only be interpreted from low gravity anomaly.

In Sungai Penuh and Muaralabuh, a half of basin which is nearest to volcanic centres is filled with mega breccia from volcano sector collapse as indicates by large blocks whose morphological appearance is similar to small domes, which observed in the toe of the volcanic slope.

3.3 Associated geothermal systems

Thermal manifestations indicate the existence of geothermal systems. All fumaroles and associated sulfate hotsprings which represent the upflow are located in the flank of volcanic centres or in the vicinity of small monogenetic domes.

In contrast, thermal manifestations along the pull-apart basin border faults are typically chloride hotspring which represent the outflow, or dilute warmsprings which either distal outflow or indicates separate deep-circulating system. It is worth to highlight that no thermal manifestations appear in the middle of the basin without any associated fault. All of them are located either in the flank of nearby volcanic centres or along the master strike-slip faults or normal faults outlining the basin.

Van Wijk et al (2017) proposed that elongated pull-apart basins with large L/W and overlapping master strike-slip faults are least likely to form cross-basinal fault, and as consequence the basin progresses continuously, followed by significant crustal thinning leads to crustal rupture. Logically, this crustal thinning should be followed by elevated heat flow inside the basin. However, significant differences in heat flow between normal and elongated basins with large L/W is not observed along the Sumatran Arc. This heat flow can be deduced from occurrence of thermal manifestations, how rigorous are they, or by subsurface temperatures. Indeed, Sarulla, the basin with extremely high L/W has largest known geothermal potential in Sumatra, but these geothermal potentials are not distributed evenly within the pull-apart basin. The most prospective geothermal system within Sarulla is Namora-i-Langit, and it is controlled by domes slightly outside the basin. The other systems within Sarulla basin, such as Silangkitan and Donotasik has lower geothermal potential, and lower temperature as well.

Instead of providing porous and permeable stratigraphic units, clay rich basin fill deposits tend to have low primary porosity and permeability. Similarly, basin fill deposits with substantial volcanic influx and dominated by competent lava and thick welded ignimbrite also have low primary porosity and permeability.

However, these competent units, which composed by central to proximal volcanic facies, can sustain permeable damage zone around intersecting faults.

Conversely, clay rich units tend to form impermeable cores within intersecting faults (Rowland and Sibson, 2004 after Caine et al., 1996). This may explain absence of thermal manifestation in the middle of the clay rich basin as it lacks of vertical permeable conduits.

The interior within the pull-apart basin is important as it creates compartmentalization within the basin. Cross-basinal fault can act as permeable pathway as in Ulubelu, or may act as compartment, as it separates eastern (Srirejo) and western geothermal system (Kalibata) in Suwoh basin. Basement high or horst in Muaralabuh provides permeability for fault-controlled circulating hydrothermal fluids, bounded by eastern and western sub-basins which are somehow tight.

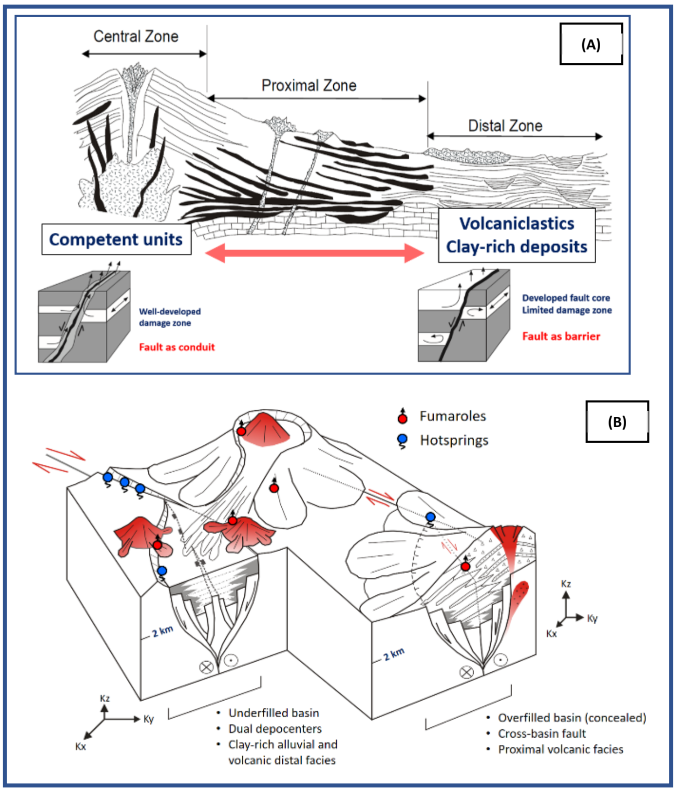

Figure 5: A. Facies model (Williams and McBirney, 1979) and the likelihood of fault permeability (modified from Rowland and Sibson, 2004); B. Conceptual model of pull-apart basins, nearby volcanic centres and thermal manifestation; red represents monogenetic domes; Kx, Ky, and Kz are permeability in three cardinal axis

4. COMPARISON TO GULF OF CALIFORNIA

In California, linkage between the opening of Gulf of California in the south and transition to transform plate boundary in the north are accommodated by series of NW-SE strike-slip faults, and subsequently creates pull-apart basins between step-over of those faults (Figure 6A). At least three known geothermal systems occur within this tectonic setting. Salton Sea and Cerro Prieto are located in the northern end of the gulf, while Las Tres Virgenes is in the central part of Baja California Peninsula, situated in the western side of one of the NW-SE transform fault series.

As situated within the pull-apart basin, thermal anomalies in both Cerro Prieto and Salton Sea are due to elevated heat flow induced by crustal thinning in active transtensional setting (Prol-Ledesma et al., 2016; Kaspereit et al., 2016). On top the thinning of the crust is followed by subsidence and rapid sedimentation of continental sediments, while in the bottom extended crust is intruded by gabbroic magma (Lachenbruch et al., 1985). Volcanic centres and extrusive domes in the vicinity of those pull-apart basins hardly affect the geothermal systems in both Cerro Prieto and Salton Sea.

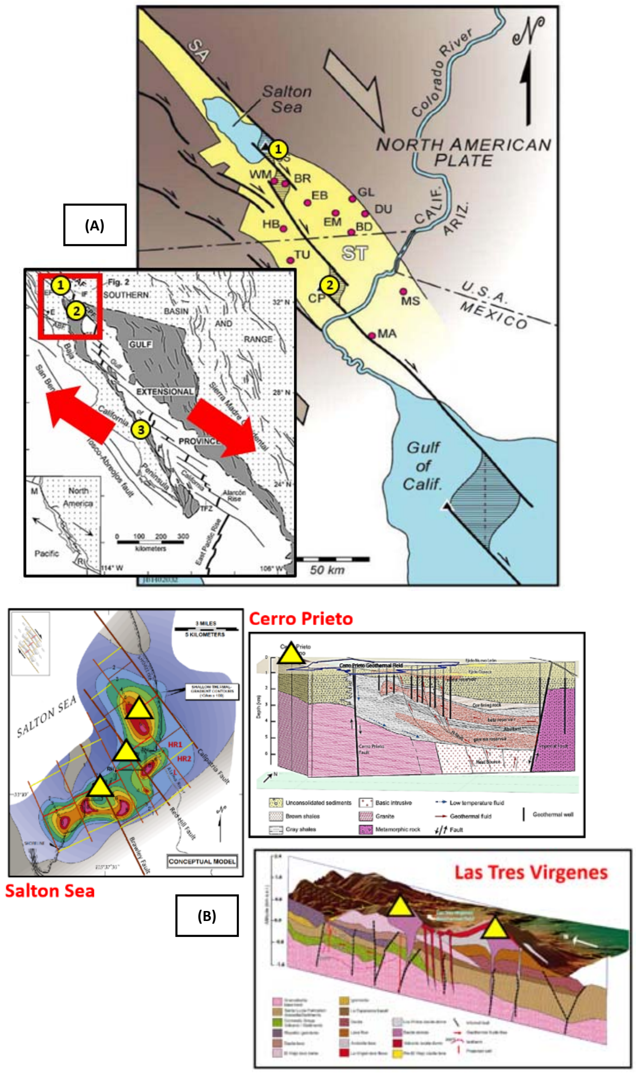

Figure 6: A. Tectonic setting of Gulf of California and location of pull-apart basins and geothermal field (Kaspereit et al, 2016); Salton Sea (1), Cerro Prieto (2), and Las Tres Virgenes (3); B. Conceptual model of Salton Sea (Karpereit et al, 2016), Cerro Prieto (Prol-Ledesma et al., 2016), and Las Tres Virgenes geothermal system (Prol-Ledesma et al., 2016), yellow triangle is volcanic centres; note that in Salton Sea and Cerro Prieto geothermal systems are contained within pull-apart basin, while Les Tres Virgenes shows typical volcanic geothermal system

Although the size of individual pull-apart basin in Sumatra and Gulf of California is comparable, contrast in geodynamic setting of those two regions creates different thermal signature within and around the basins. Salton Sea and Cerro Prieto are located in the Salton Trough, an incipient continental rift zone in transtensional setting, while Sumatran pull-apart basins were developed by highly segmented strike-slip faulting in oblique convergence.

Additionally, Las Tres Virgenes geothermal system in the south more resembles conventional volcanic geothermal system as it is strongly controlled by the intrusions associated to nearby volcanic complex. Nearby transform faults and its subsidiary structures barely influence the geothermal system.

5. IMPLICATION FOR GEOTHERMAL EXPLORATION AND FIELD DEVELOPMENT

To conclude, in a subduction-related volcanic arc such as in Sumatra, compared to magmatism and volcanism pull-apart basins are less important in influencing the geothermal systems and its potential, such as resource temperature and lateral extent. Temperature, as well as pressure, and fluid chemistry of the upflow of volcanic geothermal system is determined by the nature of shallow intrusions beneath the flank of nearby Quaternary stratovolcano or around the monogenetic domes. Moreover, Sumatran intra-arc pull-apart basins are not accompanied by crustal thinning and associated elevated heat flow within the basin outline.

The pull-apart basin plays important role in some cases when the outflow reaches the basin. Rather than controls the higher temperature upflow part, the pull-apart basin may influence the lower temperature outflow zones. Relative permeability within the pull apart basin which determined cumulatively by facies of basin fill deposits, basin compartmentalization, and fault zone permeability is important to predict the characteristics of the outflow. Although its temperature is considerably lower but in some cases widespread lateral extent and shallower depth make outflow area attractive target for field expansion in order to add power generation capacity.

As located among the active volcanic centres some parts, or for the small one the whole basin, are buried and covered by thick extrusive rocks. Therefore, it is difficult to certainly know the basin outline, let alone understanding its interior. Gravity data is really essential for this case as residual anomalies are able to predict interior geometry or estimate depth of the basin. Resistivity profile from magnetotelluric or geoelectric survey can complement the gravity data, as clay rich basin fill deposits tend to have low resistivity value.

Lesson learnt from Sumatran Arc can be applied to understand the nature of intra-arc pull-apart basin and associated geothermal system under oblique convergence such as Philippine Fault Zone or North Anatolian Fault.

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